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Optimal thermo-hydraulic performance of solar air heater having chamfered rib-groove roughness on absorber plate

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Abstract
The use of an artificial roughness on a surface is an effective technique to enhance the rate of heat transfer to fluid flow in the duct of solar air heater. However, the increase in thermal energy gain is always accompanied by increase in pumping power. This paper is concerned with optimization of roughness parameters of solar air heater based on effective efficiency criterion. Effective efficiency of a solar air heater having repeated transverse chamfered rib–groove roughness on one broad wall has been computed using the correlations for heat transfer and friction factor developed within the investigated range of operating and system parameters. Roughness parameters viz. relative roughness pitch P/e, relative groove position g/P, chamfer angle ϕ, relative roughness height e/D_h and flow Reynolds number Re, have a combined effect on the heat transfer as well as fluid friction. The thermo-hydraulic performance of an air heater in terms of effective efficiency is determined on the basis of actual thermal energy gain subtracted by the primary energy required to generate power needed for pumping air through the roughened duct. Based on energy transfer mechanism to the absorber plate, a mathematical model is developed to compute effective efficiency. The selection of the optimal values of the roughness parameters involves the comparison of the enhancement of thermal performance and the increase of pumping losses as a result of using roughness in the collector system with that of the system without roughness. The effective efficiency criterion is maximized and reasonably optimized designs of roughness are found.

Keywords: Effective efficiency, Compound-roughness, Heat transfer coefficient, Friction factor, Chamfer angle, Groove position.

1. Introduction
Solar air heaters because of their simplicity are cheap and most widely used collection devices of solar energy. The thermal efficiency of solar air heater has been found to be very poor because of their inherently low heat transfer capability between the absorber plate and the air flowing through the duct. Several designs of solar air heaters have been developed over the years in order to improve their performance. Providing artificial roughness on the absorber plate is an effective technique to enhance the heat transfer coefficient. The application of artificial roughness in the form of fine wires and ribs of different shapes has been recommended to enhance the heat transfer coefficient by several investigators [1, 2, 3, 4, 5, 6 and 7]. However, the use of artificial roughness also results in a higher friction power. It is therefore desirable that the turbulence caused by the roughened surface must be created very close to the heat transfer surface, i.e. in the vicinity of the laminar sub-layer. Hence, the efforts of researchers

have been directed towards finding the roughness shape and arrangement, which break the laminar sub-layer, enhance the heat transfer coefficient most with minimum pumping power penalty. Hence, the efforts of researchers have been directed towards finding the roughness shape and arrangement, which break the laminar sub-layer, enhance the heat transfer coefficient most with minimum pumping power penalty. Many researchers [6, 7, 8 and 9] have conducted extensive experiments with all four or two opposite roughened surface to investigate the effects of rib shape, pitch to height ratio (p/e) on heat transfer and friction factor. However, in case of solar air heater the roughness elements have to be considered in one wall only. Thus, the application of artificial roughness in solar air heater makes the fluid flow and heat transfer characteristics distinctly different than those found in case of two roughened wall surface of a rectangular channel. Therefore the solar air heaters are modelled as a rectangular duct having one roughened wall and three smooth walls, in which the flow Reynolds number ranges as 2000<Re<15000. Use of artificial roughness on the absorber plate in the form of such as protrusion of circular wire roughness [1 and 5], integral chamfered rib-roughness [3], wedge shaped rib roughened [10], square rib-groove [11] are some of the common reported methods to enhance the thermal performance of a solar air heaters. Moreover, the heat transfer coefficient between a roughened surface and flowing air is also increased due to increased turbulence of flowing air. An attempt to enhance the heat transfer is always accompanied with an increase in pressure drop, and thus the pumping power requirement is increased. It is, therefore, desirable to optimize the system to maximize the heat transfer while keeping frictional losses at a minimum possible level.

Therefore, the selection of roughness geometry has to be based on the parameter that takes into account both the thermal and hydraulic (friction) performance. In view of this, there is a need to critically examine the quantitative influence of the roughness and flow parameters to arrive at an optimum criterion so that the roughness results in maximizing the enhancement of thermal energy gain while keeping the hydraulic (pumping) losses to a minimum. This will help in introducing a design of solar air heater which is compact, efficient and most cost effective from the operational point of view.

In the present work, a methodology has been presented for thermo-hydraulic optimization of a solar air heater having its absorber roughened with chamfered rib groove roughness. Figure 1 shows the general geometry of the roughened plate having artificial roughened in the form of chamfered repeated ribs with grooves in between the ribs. The cross section of roughness can be described by the values of rib height, e, rib pitch, P, chamfer angle, ϕ of the rib and groove position between the ribs, g. In this study the rib height equals the groove depth for the entire roughened surfaces. These parameters have been expressed in the form of the following dimensionless roughness parameters:

(i) Relative roughness pitch, P/e.

(ii) Relative roughness height, e/D_h.

(iii) Relative groove position, g/P.

The minimum rib height was chosen such that the laminar sub-layer would be of the same order as roughness height at the lower flow Reynolds number. The effective efficiency has been computed for different sets of roughness parameters as reported in Table 1.

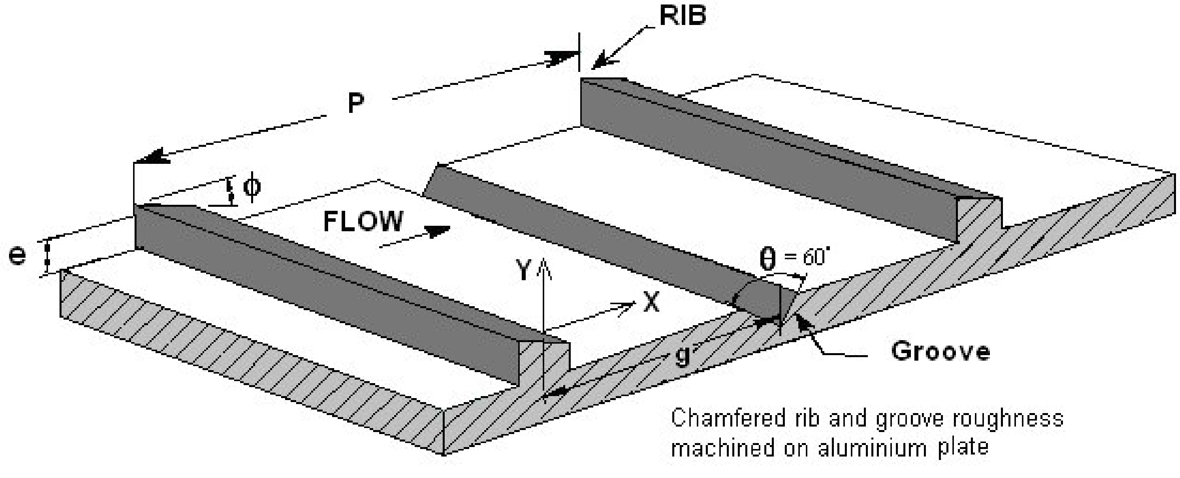

Figure 1. Rib geometry studied

2. Mathematical model for thermal performance

The performance of a solar air heater can be predicted on the basis of detailed consideration of heat transfer and fluid flow processes in the system. The performance parameters, namely overall heat loss coefficient, heat removal factor and other relevant factors and subsequently the effective efficiency can be evaluated. For this purpose a step by step procedure has to be followed. The salient features of the procedure are discussed below.

Table 1. Roughness and flow parameters and their ranges

Sl. No.	Roughness and flow parameters	Range of parameters
1	Relative roughness pitch, P/e	4.5 – 10
2	Relative groove position, g/P	0.3 – 0.6
3	Chamfer angle, ϕ, degrees	$5^o – 30^o$
4	Relative roughness height, e/D_h	0.022 – 0.04
5	Reynolds number, Re	2700 – 21000

The objective of this work is to present a methodology for optimal design of solar air heater. Results need to be presented in terms of two basic collector design parameters namely;

i. Temperature rise parameter, $\Delta T/I$ (ratio of air temperature rise across the duct, $(T_o - T_i)$ to the average intensity of insolation, I).
ii. Insolation (I).

For a given collector the calculation starts with considering a set of values of these two variable operating parameters, and proceeds with the calculation of the other parameters. Step by step procedure of calculation is given below. A computer program is developed in MATLAB for this purpose.

1- Fixed system parameters e.g. Thickness of insulation, ti, Thermal conductivity of insulation, ki, Transmittance–absorptance product, $(\tau\alpha)$, Emissivity of the absorber plate, ε_p, Emissivity of the glass cover, ε_g. Fixed operating parameters e.g. atmospheric air velocity of the air, V_w, and atmospheric temperature, T_a are selected.

2- A set of system roughness parameters namely relative roughness pitch (P/e), relative groove position (g/P), chamfer angle (ϕ) and relative roughness height (e/D_h) is selected.

3- A set of values of design parameters namely temperature rise parameter, ($\Delta T/I$) and insolation, I is selected.

4- The temperature rise of air across the duct and the outlet temperature is calculated as;

$$\Delta T = \frac{\Delta T}{I} \times I, \quad T_o = T_i + \Delta T \tag{1}$$

5- Approximate initial mean plate temperature is assumed,

$$T_{pm} = \frac{T_o + T_i}{2} + 10^o C \tag{2}$$

6- Using the value of mean plate temperature, T_{pm}, the value of the top loss coefficient, U_t, is computed using the Mullick et al [12] equation;

$$U_t = \left[\left\{ \frac{12.75\left((T_{Pm} - T_C)\cos\beta\right)^{0.264}}{(T_{Pm} + T_c)^{0.46} L_S^{0.21}} + \frac{\sigma\left(T_{Pm}^2 + T_C^2\right)\left(T_{Pm} + T_C\right)}{\frac{1}{\varepsilon_P} + \frac{1}{\varepsilon_C} - 1} \right\}^{-1} + \left\{ h_W + \frac{\sigma\varepsilon_C\left(T_C^4 - T_S^4\right)}{(T_C - T_a)} \right\}^{-1} + \frac{t_g}{K_g} \right]^{-1} \tag{3}$$

Back loss coefficient U_b, is expressed as, $U_b = ki/\delta_i$.
The edge loss coefficient, based on the collector area A_p is given as;

$$U_e = \frac{(UA)_{edge}}{A_p} = \frac{(L+W)L_c}{L\,W\,\delta_i} k_i \quad (4)$$

Consequently, $U_l = U_t + U_b + U_e$

7- Useful energy gain rate is calculated as;

$$Q_{u1} = [I\,(\tau\alpha) - U_L\,(T_{pm} - T_a)]\,A_p \quad (5)$$

8- Mass flow rate is determined from;

$$\dot{m} = Q_{u1} / C_p\,\Delta T \quad (6)$$

9- Reynolds number of flow of air in the duct is computed as;

$$Re = G\,D_h / \mu \quad (7)$$

10- The Nusselt number for the roughened surface is calculated using the correlation developed [13].

$$Nu = 0.00225\ Re^{0.92}\left(\frac{e}{D_h}\right)^{0.52}\left(\frac{P}{e}\right)^{1.72}\left(\frac{g}{P}\right)^{-1.21}\phi^{1.24}\left[exp\left\{-0.22\,(ln\,\phi)^2\right\}\right]\left[exp\left\{-0.46\left(ln\,\frac{P}{e}\right)^2\right\}\right]\left[exp\left\{-0.74\left(ln\,\frac{g}{P}\right)^2\right\}\right] \quad (8)$$

and the Dittus and Boelter correlations for Nusselt number of smooth rectangular duct given by [14], for $10^4 \le Re \le 1.24 \times 10^5$ is $Nu_s = 0.023\ Re^{0.8}\ Pr^{0.4}$. Convective heat transfer coefficient is computed as;

$$h = Nu\ k / D_h \quad (9)$$

11- The plate efficiency factor is then computed as;

$$F' = h/(h + U_L) \quad (10)$$

12- The heat removal factor based on outlet temperature, F_o is calculated as;

$$F_o = \frac{\dot{m}Cp}{A_p U_l}\left[\exp\left\{\frac{F' U_l A_p}{\dot{m}Cp}\right\} - 1\right]. \quad (11)$$

13- New value of useful heat gain is calculated as;

$$Q_{u2} = A_p F_o [I(\tau\alpha) - U_l (T_o - T_i)]. \quad (12)$$

14- The value of Q_{u1} and Q_{u2} are compared; if the difference is more than the 0.1 % of Q_{u1}, then the new value of mean plate temperature is calculated as;

$$T_{pm} = T_a + [(I(\tau\alpha) - Q_{u2}/A_p)/U_L] \quad (13)$$

Using this new value of plate temperature, steps from 8 to 16 are repeated till the difference between Q_{u1} and Q_{u2} lies within the target value. Consequently $Q_u = Q_{u1} = Q_{u2}$

15- The friction factor for the roughened surface is calculated from the correlation developed [13]

$$f = 0.00245 Re^{-0.124}\left(\frac{e}{D_h}\right)^{0.365}\left(\frac{P}{e}\right)^{4.32}\left(\frac{g}{P}\right)^{-1.124} exp[0.005\phi]\,exp\left[-1.09\left(ln\frac{P}{e}\right)^2\right]exp\left[-0.68\left(ln\frac{g}{P}\right)^2\right] \quad (14)$$

and the friction factor of smooth rectangular duct given by [15] as $1/\sqrt{f_c} = 1.7372\,ln\,(Re\sqrt{f_c}) - 0.3946$ for $4000 < Re < 10^7$ where and the Blasius relation, for $4000 \le Re \le 10^5$ is $f_c = 0.0791\,Re^{-0.25}$.

16- Using this value of friction factor, pressure drop across the duct is calculated as;

$$(\Delta P)_d = \frac{4 f L \rho V^2}{2 D_h} \tag{15}$$

and the mechanical power required to drive the air through collector is calculated as;

$$P_m = m(\Delta P)_d / \rho \tag{16}$$

17- The Thermal efficiency is calculated as;

$$\eta_{th} = Q_u / A_p I \tag{17}$$

18- Cortes and Piacentini [16] defined effective efficiency of solar air heater on the basis of net thermal energy gain obtained by subtracting the equivalent thermal energy that will be required to overcome the friction power, to flow the air through the duct, from the collector useful gain. The effective efficiency is expressed as follows:

$$\eta_{eff} = \frac{Q_u - P_m / C}{I A_p} \tag{18}$$

where, 'C' ($= \eta_f \times \eta_m \times \eta_{tr} \times \eta_{th}$) is the conversion factor accounting for net conversion efficiency (mechanical power, P_m to thermal), considering that mechanical power is obtained from a typical thermal power plant. The value of 'C' as recommended is 0.18 [= thermal power plant efficiency (= 0.344) $\times$ transmission efficiency (= 0.925) $\times$ motor efficiency (= 0.88) $\times$ efficiency of the pump (= 0.65)].

As per the calculation procedure discussed the thermal and effective efficiencies are calculated as function of temperature rise parameter and intensity of solar radiation covering the entire range of system roughness parameters as given in Table 1. For each set of calculation with a given set of design parameters (temperature rise parameter and insolation) a corresponding set of values of individual optimizing parameters, namely, thermal or effective efficiency values were determined and the optimum set of roughness parameters were identified, as the one which results the maximum value of that individual optimizing parameter for a given set of values of design parameters. This procedure was repeated with the entire range of system and design parameters. The values of optimizing parameters as function of roughness (system) and operating parameters and the optimum values of the roughness parameters as function of operating parameters are being presented and discussed below. The discussion is being utilized to draw useful conclusions regarding the optimal values of roughness parameters of the chamfered rib-groove compound roughness.

3. Results and discussion

Values of the effective efficiency for different roughness parameter have been obtained numerically using the above approach for smooth as well as for chamfered rib groove roughened surfaces. The values of the effective efficiency have been obtained for varying temperature rise parameter in the range of 0.003 to 0.027 K/m^2 W with a constant value of the insolation of 800 W/m^2 and ambient air temperature of 300 K. Figure 2 has been drawn to show the effect of the Reynolds number on the thermal energy gain and the pumping power for a typical roughened surface. It may be observed that, at higher Reynolds numbers, the rate of increase in pumping power is very high, while the rate of the useful energy gain becomes nearly constant. It is also observed that at lower Reynolds numbers, the rate of increase in power required to force the air through the duct is low, while the rate of useful energy gain is substantial. Therefore, with the increase in Reynolds number, a stage is reached where we get the optimum value of energy gain. It is also evident from the figure that at higher value of Reynolds number, the benefit of net energy gain might eventually vanish.

The effective efficiency of smooth as well as roughened absorber plate solar air heaters has been computed on the basis of method proposed by Cortes and Piacentini [16]. The effective efficiency of solar air heater is considered as has strong dependence on parameter of roughness element i.e. the relative roughness pitch (P/e), relative groove position (g/P), chamfer angle (ϕ), relative roughness height (e/D_h) and flow Reynolds number (Re) or temperature rise parameter. There is a considerable enhancement in the effective efficiency of solar air heaters having roughened duct provided with chamfered rib-groove roughness compared to that of smooth duct. Plots have been prepared to show the effect of roughness parameters on the effective efficiency for fixed values of other parameters. Figure 3 to 6 shows the effect of relative roughness pitch (P/e), relative groove position (g/P), chamfer angle (ϕ) and relative roughness height (e/D_h) respectively on effective efficiency for the optimal values of other roughness parameters. It can be observed from these figures that initially effective efficiency increases with the increase in Reynolds number (or decrease in temperature rise parameter), attains maxima and thereafter it decreases. The reason may be due to dominance of mechanical power, which is required to overcome the frictional forces in the duct at higher Reynolds number. Further it is also observed that the Effective efficiency of smooth solar air heater is better than the roughened solar air heaters in the range of very high Reynolds number.

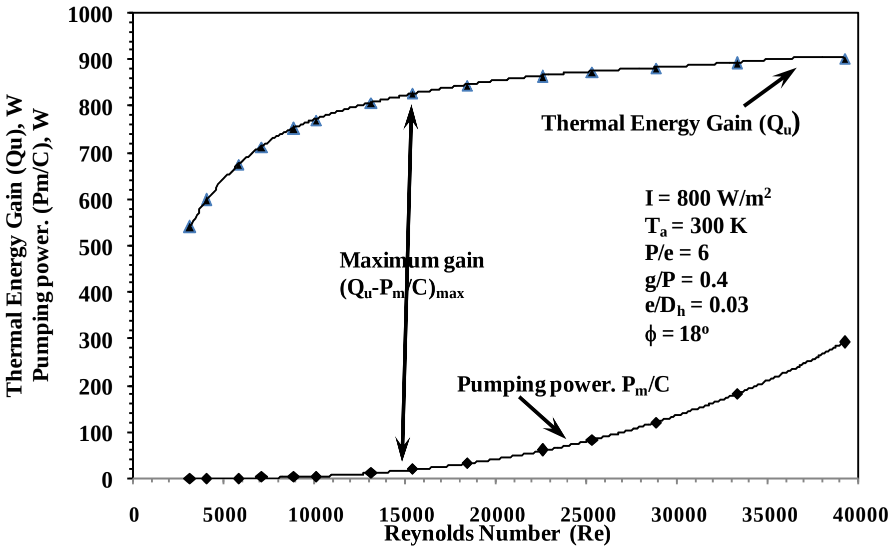

Figure 2. Effect of Reynolds number on thermal gain and pumping power.

Accordingly the focus of presentation and discussion is based on performance as a function of operating parameters i.e. ΔT/I and I. It is obvious that, as the mass flow rate increases, the temperature rise parameter decreases because temperature rise is inversely proportional to the mass flow rate. It is observed from Figure 3 that for temperature rise parameter (ΔT/I) higher than of 0.01 K/m^{2}W, relative roughness pitch of 6 shows the highest effective efficiency whereas for temperature rise parameter of lower than 0.004 K/m^{2}W the smooth collector shows the best performance while for the temperature rise parameter in the range from 0.004 to 0.007 K/m^{2}W, relative roughness pitch of 4.5 yields the highest effective efficiency. Figure 4 reveals that from thermal efficiency point of view the solar air heaters having chamfered rib groove roughened absorber plate perform better than that with the smooth conventional plate for the entire range of operating parameters investigated in the present study. Simultaneously it can also be seen that the increase in thermal efficiency compared to that of smooth conventional solar air heater is much higher in lower mass flow rate. From Figure 3 it is also seen that as the temperature rise parameter decreases, the effective efficiency of all the surfaces first increases, attains a maxima and then decreases. It is also evident that the effective efficiency of a smooth collector attains higher values as compared to roughened surface corresponding to low temperature rise parameter range. Therefore, in the low temperature rise parameter range, roughened surfaces are not beneficial in terms of effective efficiency, although they are beneficial from thermal performance point of view. The figure also indicates that the effective efficiency increases moderately with decrease in the temperature rise parameter in the higher range, whereas for lower values of the temperature rise parameter the effective efficiency decreases sharply. These trends can be explained based on the fact that for lower flow rates, the rise in temperature shall be higher while the frictional losses would be lower, resulting in higher effective efficiency. For the cases, where the rise in temperature is lower, the mass flow rate would be higher; resulting in significant frictional losses and hence more pumping power would be needed. This would result in lowering the effective efficiency sharply for large values of flow rates.

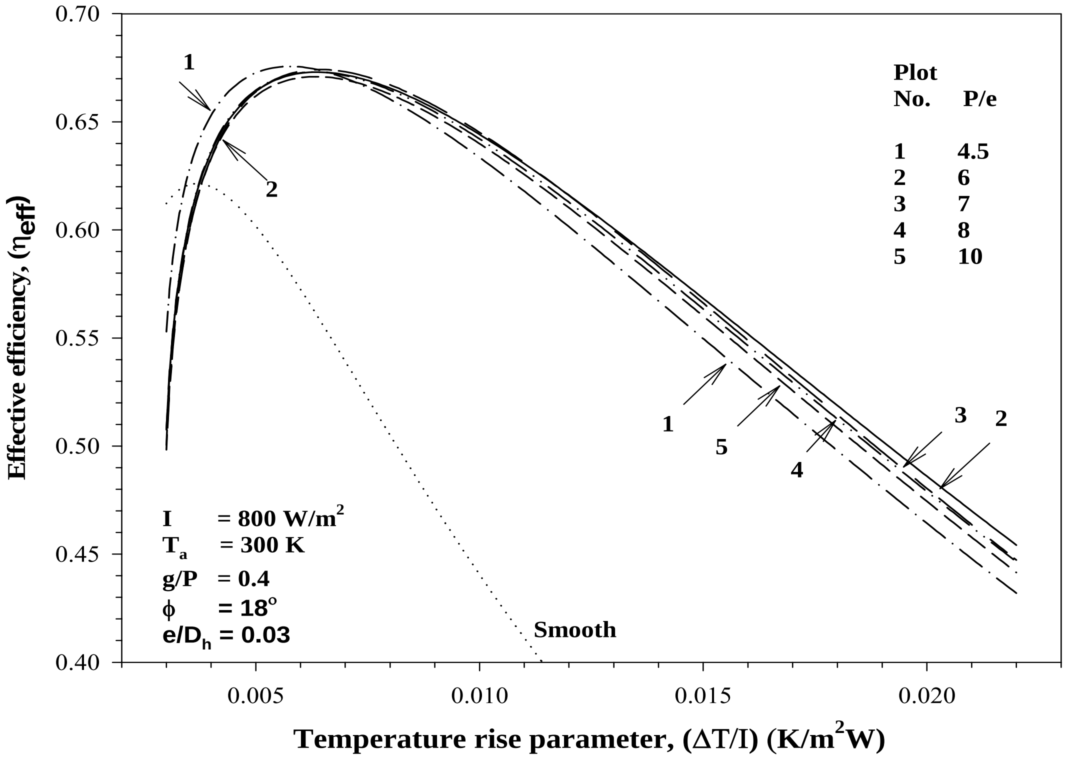

Figure 3. Effect of relative roughness pitch on effective efficiency.

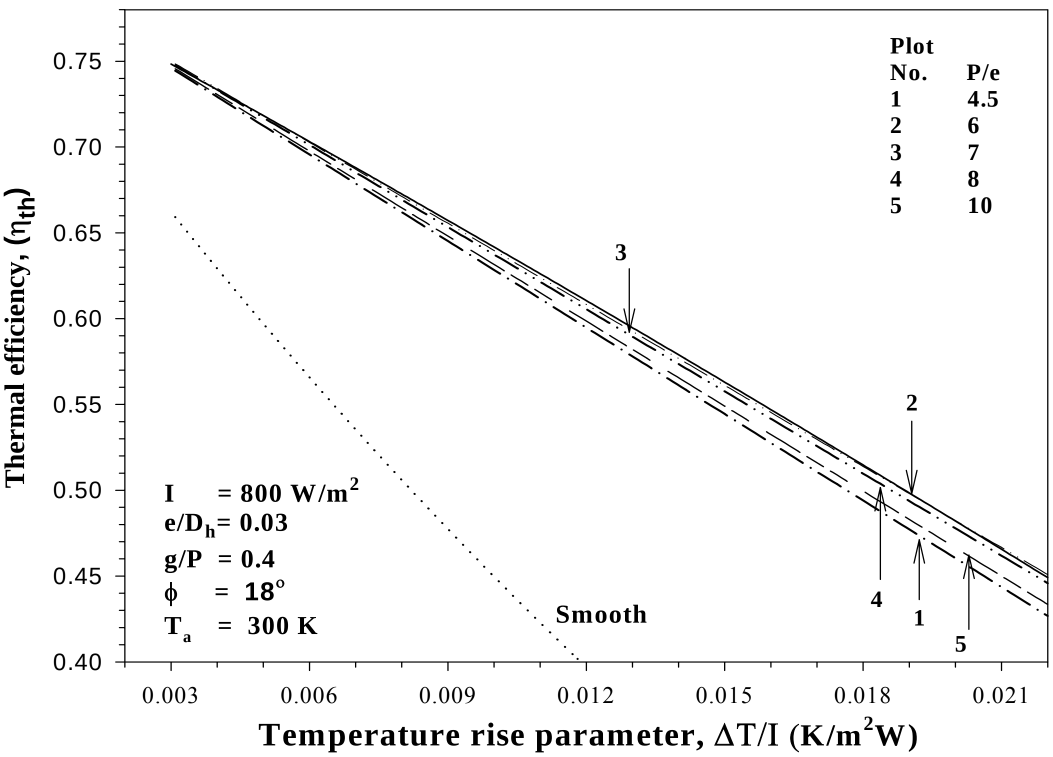

Figure 4. Thermal efficiency as function of temperature rise parameter and relative roughness pitch.

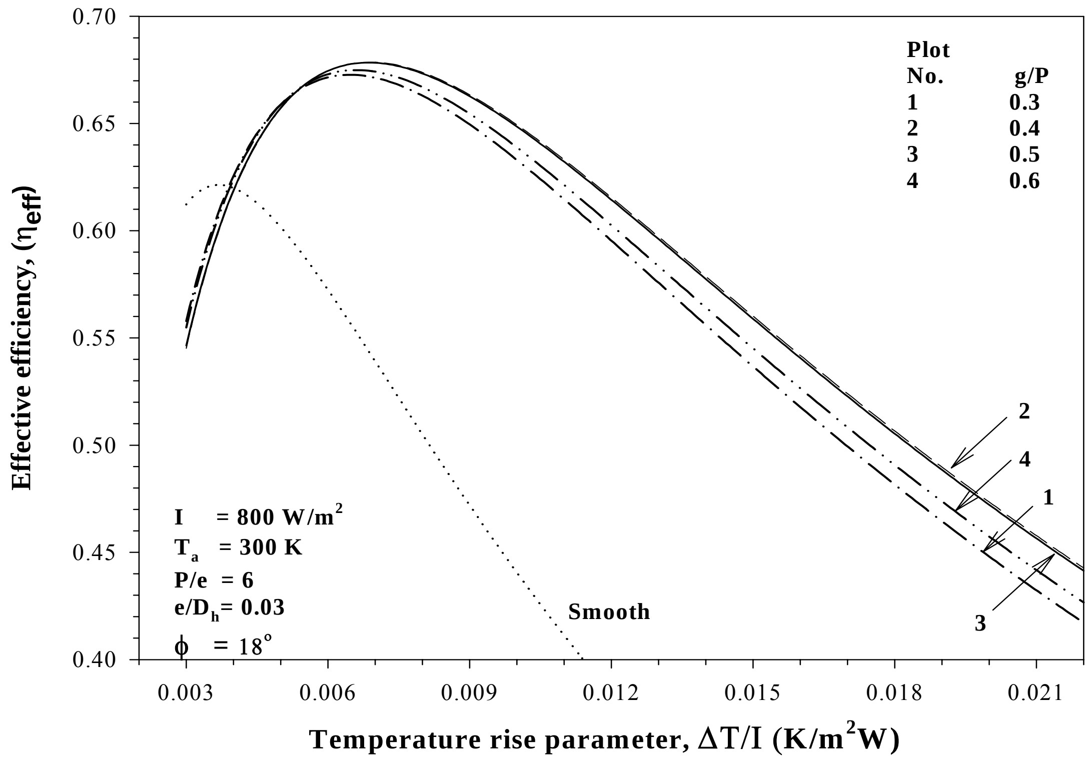

Figure 5. Effect of relative groove position on effective efficiency.

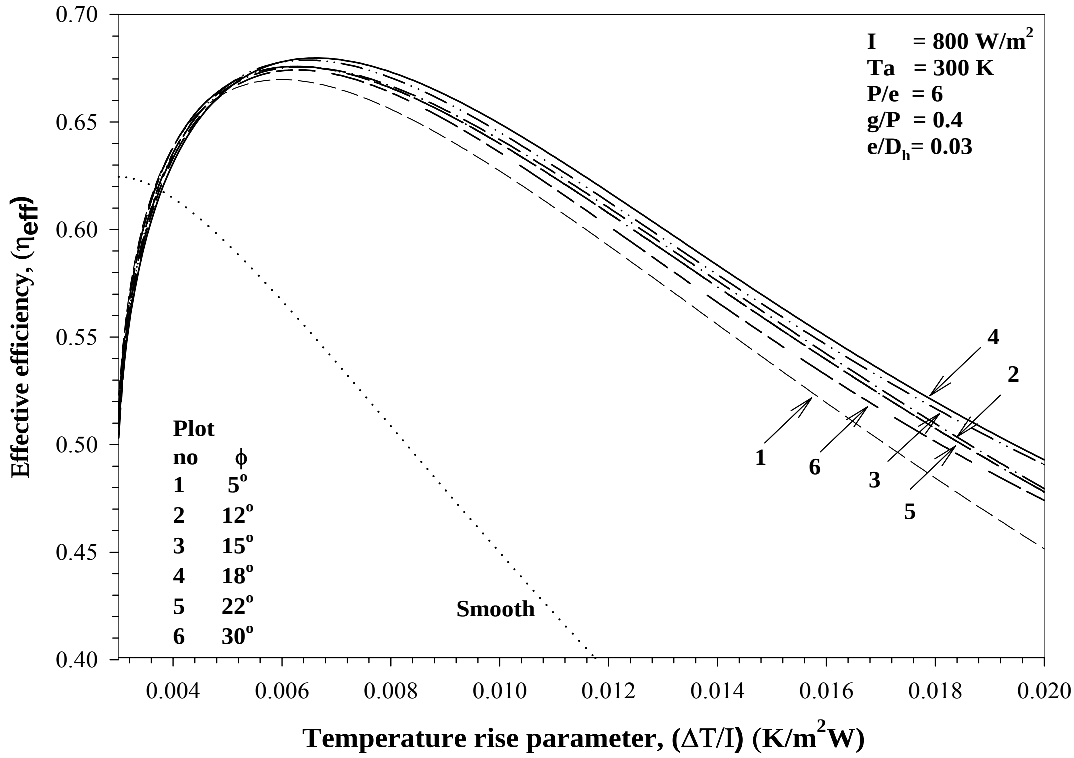

Figure 6. Effect of chamfer angle on effective efficiency.

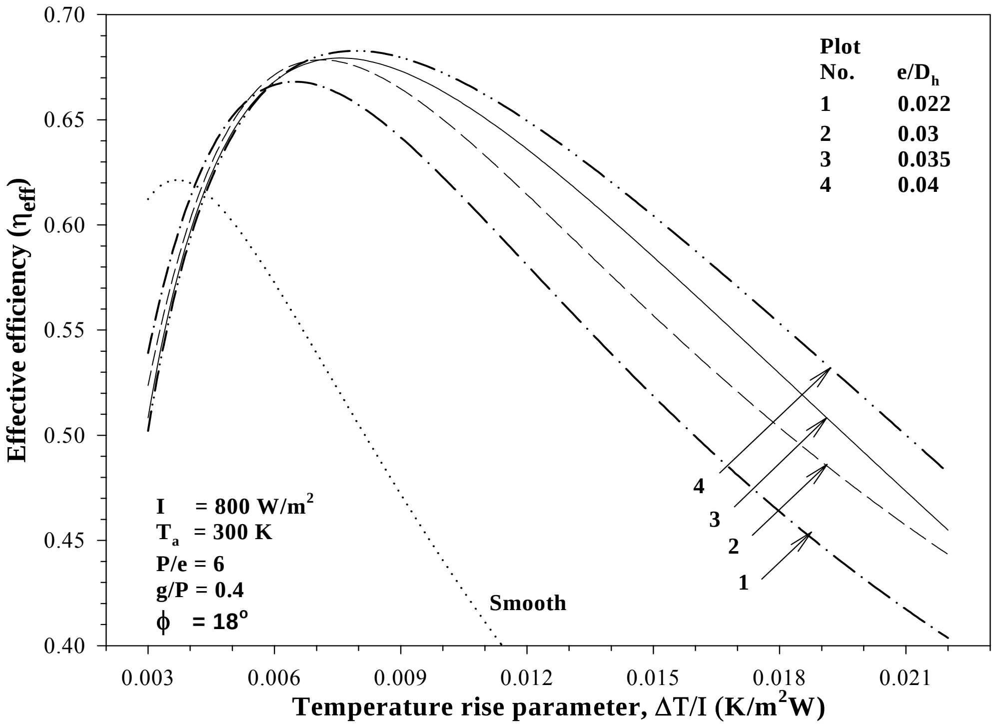

Figure 7. Effect of relative roughness height on effective efficiency.

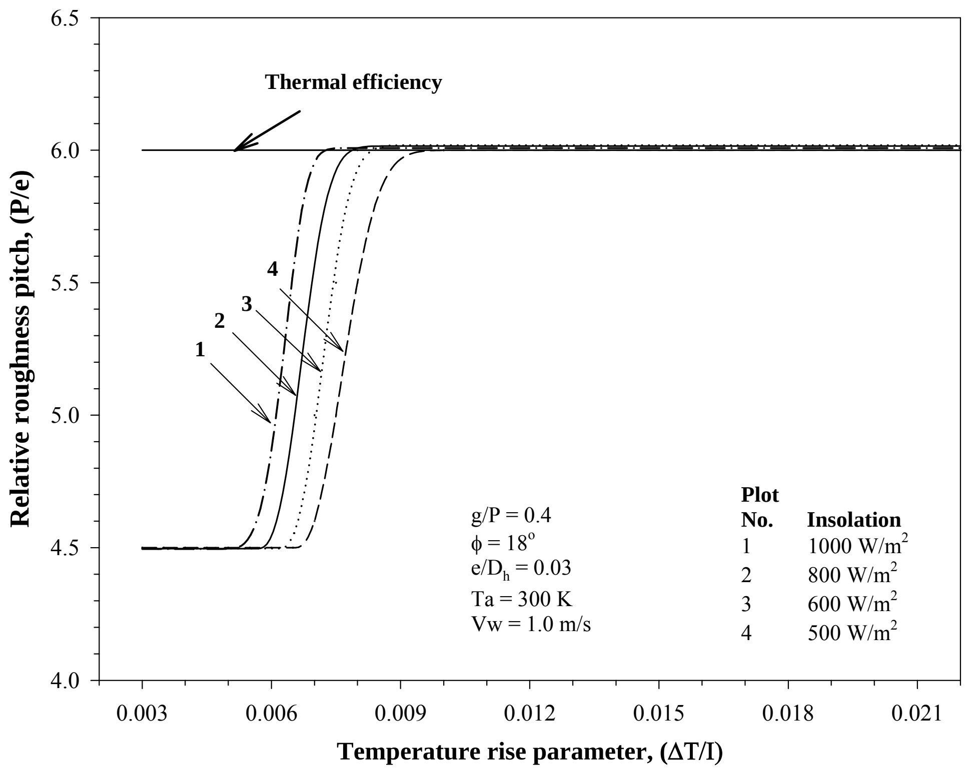

Figure 8. Optimum values of relative roughness pitch on the basis of thermal and effective efficiency criterion.

The corresponding critical values for temperature rise parameter as seen from Figure 5 are 0.004 K/m^2W, below which smooth collector shows maximum efficiency, 0.0055 K/m^2W up to which a groove position of 0.3 and 0.006 K/m^2W, beyond which a groove position value of 0.4 yields highest effective efficiency values. Similarly Figure 6 and 7 have been drawn to show corresponding parametric dependence of chamfer angle and relative roughness height values respectively. It is also observed that the effective efficiency corresponding to the higher values of roughness height is better in the higher range of temperature rise parameter; however the value of effective efficiency is reversed in the lower range of temperature rise parameter. This effect can be attributed to the fact that at higher temperature rise parameter, the increase in friction losses in the duct is insignificant with increase in relative roughness height, while the increase in heat transfer from roughened surface is quite substantial due to increase of turbulence in the vicinity of roughened surface.

It can be seen that no single value of a roughness parameter or a set of values of a roughness parameters can yield the highest effective efficiency (or the best thermo-hydraulic performance) in the entire range of operation. Plots have been prepared to show the corresponding optimum values of relative roughness pitch, relative groove position, chamfer angle and relative roughness height respectively as function of temperature rise parameter and insolation. The plot of optimum values of roughness parameters that corresponding to maximum effective efficiency for a given set of values of temperature rise parameter and intensity of solar radiation are shown in Figures 8, 9, 10 and 11 respectively.

Figure 8 shows the plot of optimum relative roughness pitch as a function of temperature rise parameter for different values of insolation. It is seen that for effective efficiency criterion the values of temperature rise parameter higher than about 0.009 K/m^2W, the value of relative roughness pitch of 6 represents the optimum condition for all values of insolation whereas, the values of temperature rise parameter lower than about 0.005 K/m^2W, the relative roughness pitch of 4.5 represents the optimum condition. For the value of temperature rise parameter in the range of $0.005 < \Delta T/I < 0.009$ K/m^2W, optimum relative roughness pitch is a function of insolation and temperature rise parameter, and the value of optimum relative roughness pitch increases with the increase in the value of insolation. On the basis of thermal efficiency criteria it can be seen that for the entire range of temperature rise parameter the optimum values of relative roughness pitch is 6.0.

Similarly, Figures 9, 10 and 11 have also been prepared to show the corresponding optimum values of relative groove position, chamfer angle and relative roughness height respectively as function of temperature rise parameter and insolation. The optimum values of roughness parameters determined on the basis of effective efficiency can be seen to be strong function of temperature rise parameter and insolation. On the other hand based on thermal efficiency criterion a single value of roughness geometry represents the optimal roughness.

Above discussion reveals that there exists a set of optimum roughness parameters which optimizes the performance of the solar air heater and this set of parameters comprising of relative roughness pitch, relative groove position, chamfer angle and relative roughness height is a strong function of operating parameters namely temperature rise parameter and insolation. The set of these optimum parameters (based on effective efficiency criteria) can be found from Figures 8, 9, 10 and 11. Figure 12 can be used to obtain the values of thermal efficiency of a collector using roughness elements represented by optimum set of roughness parameters. This thermal efficiency value can then be used to determine the optimum area of collector for a given requirement of energy collection rate.

The following example explains the simple optimum design methodology for the solar air heater having absorber plate roughened with chamfered rib-groove roughness. For a typical residential solar air heating system, the heated air temperature can be specified to be approximately at 20^oC. For an average solar radiation intensity of 800 W/m^2 and ambient (inlet) temperature of 10^oC, the temperature rise across the collector will be 10^oC and the temperature rise parameter will works out to be 0.0125 K/m^2W. Figures 8, 9, 10 and 11 have been used to arrive at the set of optimum values of the system parameters as: relative roughness pitch $(P/e) = 6$, relative groove position $(g/P) = 0.4$, chamfer angle $(\phi) = 18^o$, relative roughness height $(e/D_h) = 0.04$.

Figure 12 has been used to obtain the values of thermal efficiency for the solar air collector roughened with optimum roughness, this works out to be 0.56. In order to determine the enhancement in the performance as a result of providing optimum artificial roughness, the corresponding thermal efficiency for the conventional smooth solar air heater for the same operating parameters has been determined which works out to be 0.38. Therefore, a solar air heater roughened with optimally chamfered rib–groove roughness operated under that temperature rise parameter of 0.0125 K/m^2W shows a 47.4 % enhancement in the thermal efficiency.

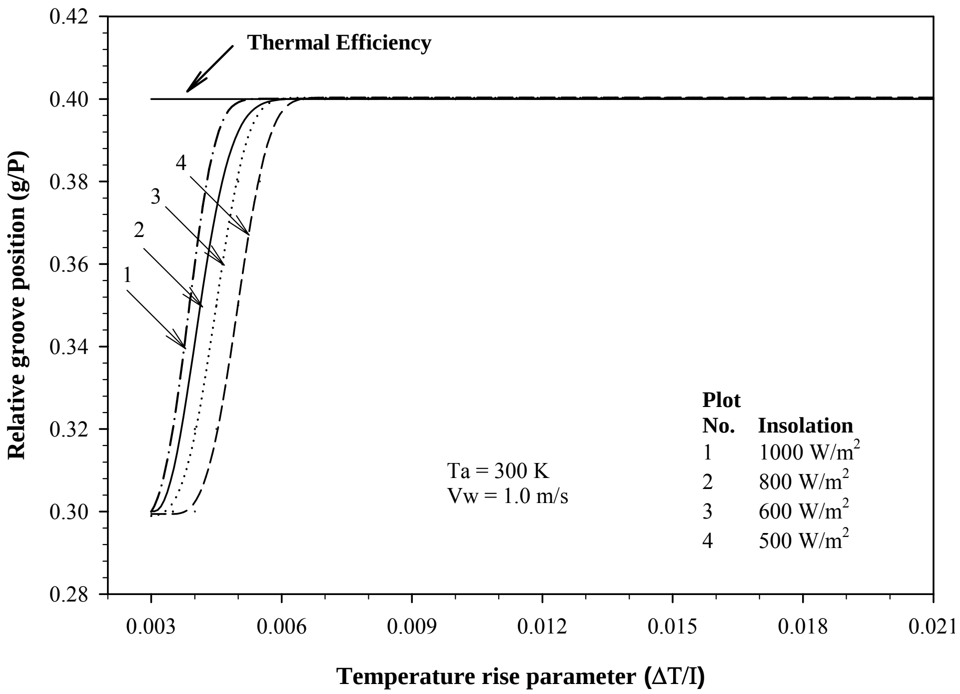

Figure 9. Optimum values of relative groove position on the basis of thermal and effective efficiency criterion.

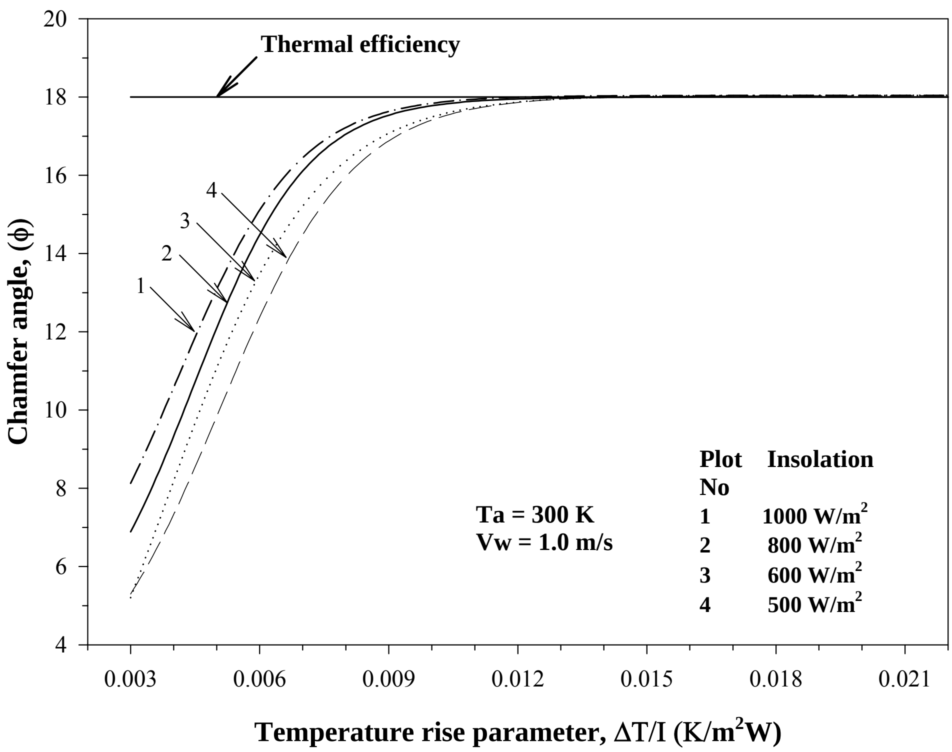

Figure 10. Optimum values of chamfer angle on the basis of thermal and effective efficiency criterion.

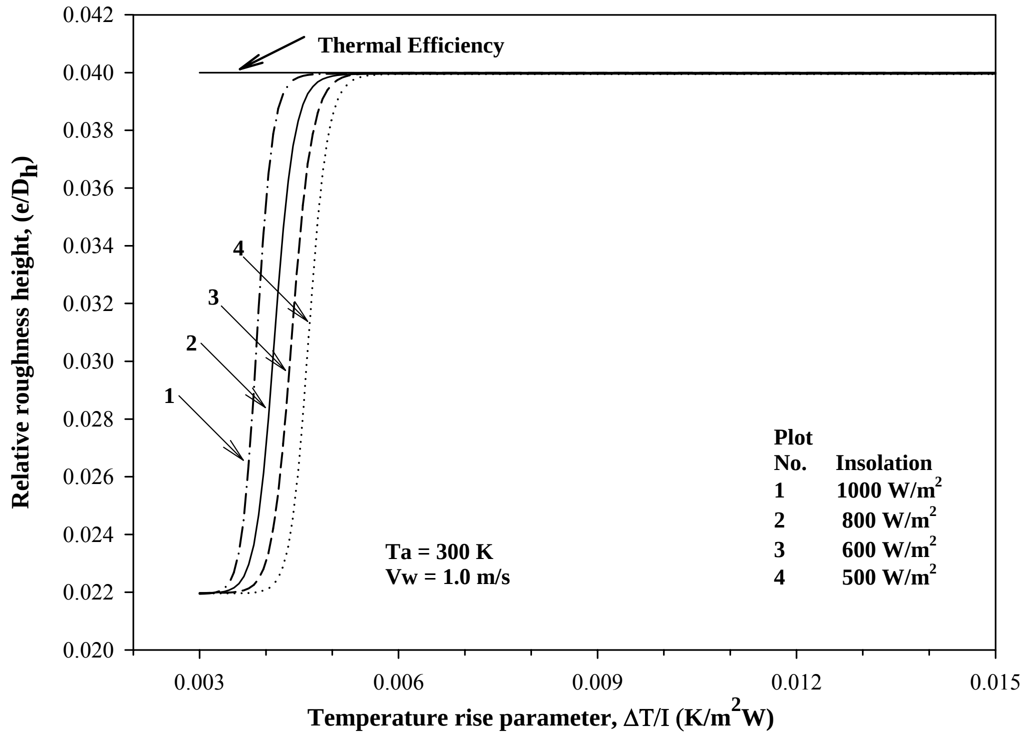

Figure 11. Optimum values of relative roughness height on the basis of thermal and effective efficiency criterion.

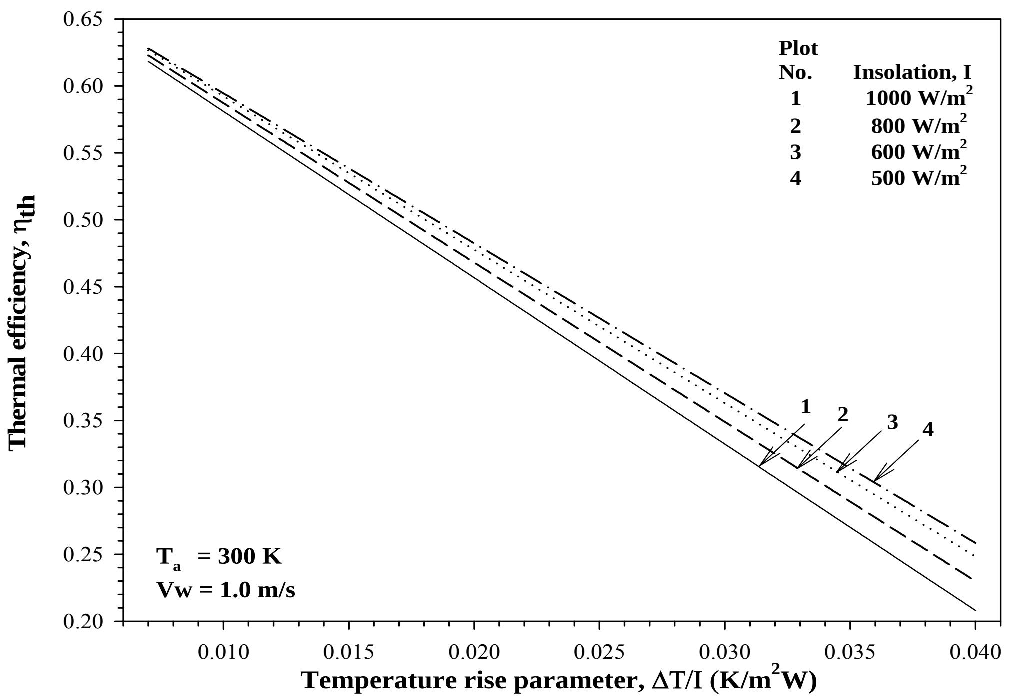

Figure 12. Thermal efficiency as function of temperature rise parameter and insolation for optimum roughness parameters.

4. Conclusion

1. Thermo-hydraulic investigations of solar air heater having absorber plate provided with chamfered rib – groove roughness indicate that the thermal gain of such collectors is relatively higher as compared to smooth collectors with nearly same pressure drop penalty. Solar air heaters with absorber plate roughened with chamfered rib – groove roughness have been found to have a better effective efficiency as compared to conventional smooth air heaters.
2. The Reynolds number (or temperature rise parameter) has been found to be a strong parameter affecting the effective efficiency. It has been found that there exists an optimum value of effective efficiency for a given roughness parameter.
3. It is found that for higher values of the temperature rise parameter, the effective efficiency values closely follow the thermal efficiency values, whereas there is an appreciable difference in the lower range of temperature rise parameter values.
4. It is seen that the thermal efficiency criteria for the entire range of operating parameters yield a single set of optimum values of roughness parameters, eg. P/e = 6, g/P = 0.4, $\phi = 18^{o}$ and e/D_h = 0.04.
5. There exists a set of optimum values of roughness parameters which yields highest effective efficiency corresponding to a given set of operating conditions.
6. It is seen that for a range of temperature rise parameter the roughness parameters are dependent on temperature rise parameter and insolation, while beyond that range of temperature rise parameter a single value of roughness parameter represents the optimum value.

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